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Comparing the knowledge bases of wind turbine firms in Asia and Europe: patent trajectories, networks, and globalisation

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Abstract

This study uses patent analyses to compare the knowledge bases of leading wind turbine firms in Asia and Europe. It concentrates on the following aspects: (a) the trajectories of key technologies, (b) external knowledge networks, and (c) the globalisation of knowledge application. Our analyses suggest that the knowledge bases differ significantly between leading wind turbine firms in Europe and Asia. Europe's leading firms have broader and deeper knowledge bases than their Asian counterparts. In contrast, Chinese lead firms, with their unidirectional knowledge networks, are highly domestic in orientation with respect to the application of new knowledge. The Indian lead firm Suzlon, however, exhibits a better knowledge position. While our quantitative analyses validate prior qualitative studies it also brings new insights. The study suggests that European firms are still leaders in this industry, and Asian lead firms are unlikely to create new pathways that will disrupt incumbents in the near future.

Key words: Patent analysis, wind turbine firms, knowledge base, trajectory, knowledge flow, network analysis, Asia and Europe

1. Introduction

The wind power industry plays a key role in the efforts of European and Asian countries to promote renewable energy. Wind energy, as the most commercialised and successful type of renewable energy currently available (Lema et al., 2014), has experienced a stable and high average growth in the past 15 years. Led by European firms for many years, the recent rise of emerging economies has made them significant competitors in the global wind market. There is a debatable assumption that these rising powers might build specific knowledge bases, and even challenge the traditional leaders (most of whom are European firms) through future leapfrogging.

Firms' knowledge bases are considered significant in relation to competitiveness and future pathways (Nesta and Saviotti, 2005).¹ Considering knowledge as competitiveness, a strong knowledge position may offer advantages that increase opportunities for sustainable development, market leadership or even leapfrogging (Pavitt et al., 1997). A strong knowledge position may also bring bargaining power and serve as a source of knowledge-based revenue (Bekkers et al., 2002). From an evolutionary perspective, firms' choices regarding key technologies and other settings may influence future pathways (Dosi, 1982). Such path dependency may also imply that the knowledge bases of different firms do not necessarily converge toward a single best practice, as the firms' specifics and the contextual embeddedness of such evolutionary processes may result in diverse trajectories (Schmitz and Altenburg 2015). There has been limited research examining this.

These knowledge base concepts can be characterised by various methodologies, and a patent-based lens is frequently used. In recent years, patent profiles have been increasingly employed to understand knowledge trajectories (Ernst, 2003; Damrongchai et al., 2010). Others have used essential patents to map or forecast future pathways (Jeong and Yoon, 2014). On the other hand, assuming that knowledge reflects competitiveness, some recent research has used patent counts to explicate the core technologies and portfolio strategies (Tseng et al., 2011; Ju and Sohn, 2014). In more advanced cases, patent network has been used to analyse the global knowledge flow, such as learning and spillover within industries and across national borders (Bekkers and Martinelli, 2012).

Given the success of these patent-based approaches, it may prove promising to extend these quantitative methods to explore whether Asian wind firms might build a unique knowledge base for technological leapfrogging. We believe that doing so may offer a unique perspective with quantitative estimates, as other contemporary researchers are exploring international comparisons of wind turbine manufacturers from a qualitative perspective (Lema et al., 2014; Dai et al., 2014). In this study, our goal is to integrate and use a set of patent-based methodologies to address the following question: *To what extent and how do the patent knowledge bases differ between leading wind turbine firms in Asia and Europe?* We also explore what these differences between knowledge bases tell us about the global competition between leading firms and the policy implications. This study focuses on three aspects related to examining firms' knowledge bases: the trajectories of key technologies (measured by patents), external knowledge networks for patents, and the globalisation of

¹ Knowledge bases may refer to the resources and capabilities to produce ideas, thoughts, programmes, and products through creations and innovations and turn them into economic value and wealth.

knowledge applications, with a focus on patenting efforts. Six wind turbine firms serve as representative cases in Asia and Europe: Goldwind (China), Mingyang (China), Suzlon (India), Enercon (Germany), Siemens (Germany), and Vestas (Denmark).

The remainder of this paper is organised as follows. Section 2 provides a narrative of the wind industry and its leading firms. Section 3 discusses our methodology. Section 4 compares the cases. Section 5 discusses the findings and concludes the paper.

2. Wind turbine industry and leading firms: narratives of key knowledge activities

The wind energy industry has achieved rapid growth, and will continue to grow. The global share of electricity generation from wind could reach 12% by 2050 (IEA, 2009). Initially, developed countries led the attempts to develop wind power energy in terms of both the technology and market occupation for more than 30 years (Lema et al., 2014). However, in the past decade, the distribution of the world wind energy market reflected obvious strong shift in production capacity and deployment scale. In the late 2000s, emerging economies such as China and India began to catch up and rapidly gained a large market share (Dai et al., 2014; Narain et al., 2014).² In 2013, both China and India had wind turbine firms that were listed in the top five market owners – Goldwind was number two and Suzlon was number five – in terms of accumulated installation capacity.³ Thus, China and India may play more significant roles in wind knowledge activities.

Here, we specifically focus on the key dimensions of knowledge bases that may highlight the knowledge differences – as aforementioned, the differences may imply dissimilar future pathways. First, the trajectories of key technologies are primarily important (Lema et al., 2014) to firm's knowledge bases. They are important because they determine the size, shape and direction of firm decisions about key technologies and patenting strategies. Second, the external knowledge network and firms' relative position is also a critical dimension, while knowledge transfer (flow) and collaboration activities can reflect network positions (as an innovation leader or follower) and are essential to develop the bases (Bekkers and Martinelli, 2012). This is particularly important as China and India have depended for many years on technology transfer and technology collaboration for accessing state-of-the-art wind energy technology, while indigenous innovation is a relatively new phenomenon. In addition, the globalisation attempt is another significant dimension, and the globalization of knowledge applications can provide insights to interpreting firms' ambitions towards global markets (Dai et al., 2014). This provides evidence about lead markets and firm leadership on an international level. Thus, we will examine these three knowledge dimensions, and the following narratives may provide a reference point for the understanding of lead firms' knowledge bases.

Trajectories of key technologies. In the wind power industry, the key technologies of

² Having installed 17.63 gigawatt/s (GW) wind turbines in 2011, China became the global leader in terms of both annual and total installation capacity, reaching 62.36 GW and accounting for 40% of the global installed capacity (CWEA, 2013). In India, the total installed wind power capacity reached 11.75 GW by the end of March 2010, up from 1.63 GW in 2001-02, with an average annual growth of 28.6% (Narain et al., 2014).

³ In 2013, the top 15 leading firms (in terms of market share) were: Vestas (13.2%), Goldwind (10.3%), Enercon (10.1%), Siemens (8%), Suzlon (6.3%), General Electric (GE, 4.9%), Gamesa (4.6%), Guodian United Power (3.9%), Mingyang (3.7%), Nordex (3.4%), XEMC (3.2%), Envision (3.1%), Dongfang Electric (2.3%), Sinovel (2.3%), and Shanghai Electric (2.2%) (The World Wind Energy Report, 2013). Some of the top firms are briefly introduced in Section 3.

wind turbines consist of various aspects (Lema et al., 2014). Wind turbine design may be the most important indicator for studying the technological trajectories, because such designs can be viewed as platforms supporting continuous incremental innovations. There are two major **platforms** for wind turbines: gear and gearless models. The gear model can be traced back to the early 1900s in Demark as the 'Danish Design' (Lema et al., 2014). To date, the gear model still occupies the majority of the wind turbine market share, e.g. 72% in 2013 (BTM Consult, 2013). Vestas maintains the gear-model with a platform called 'dual-fed induction technology (DFIT)'; meanwhile, most wind manufacturers (e.g. Gamesa, Suzlon, etc.) are following this path. The other major platform is the gearless or 'DD' model (DD), which accounts for a smaller but steadily increasing market share – from 14% in 2007 to 28% in 2013 (BTM Consult, 2013). The development of the DD technology was also driven by European firms (mostly German), and initially developed by Enercon. Based on Enercon's direct drive design, the permanent magnets direct drive (PMDD) has also been developed by German companies such as Vensys and Siemens (offshore). China's Goldwind, after collaborating with Vensys, has participated in this group and significantly contributed to the increase in market shares since 2006.

The other recent indicator is the turbine size, mainly due to **emerging offshore technologies**, and all of the world's leading manufacturers are competing. For example, Enercon developed 126 7.5-megawatt/s (MW) offshore turbines in 2007, and Vestas had 8.0-MW offshore turbines in 2010. In addition, larger up-scaled turbines (10-20 MW) are being explored by lead companies such as Enercon, Vensys, etc. (Lema et al., 2014). On the other hand, Chinese manufacturers have also participated in this race, with prototypes for 8 to 10-MW turbines since 2011 (Dai et al., 2014).

Other essential technological aspects may be related to those turbine technologies that **complement** the above platforms' reliability and quality when concerned with deployment, possibly including control technologies and grid connections. In this regard, it has been argued that high-tech firms benefit from diverse technology portfolios whereas low-tech firms need to have higher concentrations (Lichtenthaler, 2010). However, there has been limited inquiry into the specific wind sector. Furthermore, it has been argued that Asian wind turbine firms are specialised in developing **customised turbines**, such as high-altitude compatible, sand-proof, etc. (Dai et al., 2014). This also requires empirical examination.

Knowledge transfer (flow) and collaboration. Knowledge flow and collaboration play key roles in developing knowledge bases (Bekkers and Martinelli, 2012). Specifically, in the wind turbine sector, **knowledge flow** in terms of learning and spillover is prominent. European firms started earlier, in the 1970s, and thus have been first movers in research and development (R&D) and frontier wind technologies that create spillover knowledge. India started local manufacturing in the mid-1990s and China in the late 1990s. As latecomers, Indian and Chinese wind turbine firms strove to catch up with the learning, and benefited significantly from technology transfer and cooperation in the form of foreign aid, joint ventures, licensing and international acquisitions (Lewis, 2013). For example, some researchers have found that most Chinese turbine manufacturers (26) have technological links with European (mostly German) knowledge-intensive firms (Schmitz and Lema, 2014). Specifically, Goldwind has conducted joint development with Vensys and received licensing from Jacobs/Repower (Goldwind later acquired Vensys in 2008) while Mingyang engaged in joint development with Aerodyn (Lewis, 2013). Meanwhile, Indian firms have also been very active in acquiring external knowledge through the network. In the late 2000s, Suzlon in India bought the Sudwind R&D team in Germany and a blade-manufacturing factory in Amsterdam. Suzlon then produced turbines for the Indian market by leveraging their

acquired expertise abroad (Narain et al., 2014). These knowledge activities however are rather anecdotal and require empirical data for in-depth inquiries.

Collaboration is also significant for knowledge bases. Innovative firms can leverage alliances to access intellectual resources that promote more efficient R&D in this open innovation era (Chesborough, 2003). Wind firms also collaborate within the networks. According to Lema et al. (2014), the network may be the value chain that produces and assembles a wind turbine's components between major wind manufacturers (e.g. Vestas, Enercon, etc.) and specialised component suppliers (e.g. LM Glasfiber is the world's largest manufacturer of rotor blades). Collaboration may also happen beyond component suppliers and may involve project developers. For example in Europe, Ramboll offers engineering and planning services, including structural design, to the offshore wind industry (Lema et al., 2014). This also requires empirical enquiries.

Globalisation attempts. In this globalisation era, many wind turbine firms are attempting to or have already become international firms with a global reach. For example, Vestas is no longer a 'Danish Firm' but rather a global firm that only sells a small fraction of its wind turbines to Denmark (Lema et al., 2014). For Vestas and Enercon, the growth comes from other markets outside Europe and their R&D is globally organised, although firmly coordinated from Denmark and Germany (BTM Consult, 2013). Siemens, Gamesa and GE are considered to be regional suppliers that produce technologies within their home countries but send active exports to the global markets. Chinese and Indian wind firms are still rather domestic, but are striving to participate in the globalisation activities in addition to their previous efforts toward international knowledge transfer. Suzlon acquired Repower in 2007 for global market access and technologies – a rare acquisition between the mainstream wind turbine manufacturers. Goldwind, however, acquired Vensys (a German design firm) in 2008 and became the largest exporter of wind turbines in China (approximately 90%) in 2011 (Dai et al., 2014).

3. Methodology

3.1 Research design and case selections

Following Yin (2003), we selected six leading firms as representative cases (**Table 1**) for our cross-case comparison using a patent-based analysis. The analysis followed the methodological success of prior patent studies (see 3.2), focusing on the trajectories of key technologies, knowledge networks (e.g. knowledge flow and collaboration), and globalisation patent families.

Table 1 Sample wind manufacturers in Asia and Europe

	Goldwind	Mingyang	Suzlon	Enercon	Vestas	Siemens
Employment size	4162	4600	10000	13000	17778	370000
Age (years)	16	8	19	30	33	167
Market share (2012)	6.0%	2.7%	7.4%	8.2%	14%	11.0%
Patents (basic, by 2012)	231	200	314	337	1061	294
Patents (family, by 2012)	233	228	1772	4826	5093	453
SCI papers (by 2012)	2	0	14	3	105	156
Country	China	China	India	Germany	Denmark	Germany

The selection process was purposive rather than random. A theoretical sampling procedure applied two case selection criteria: 1) the firms are leading wind manufacturers in their home countries with a global reach; and 2) they have specific knowledge competitiveness that can be analysed using patents. Hence, we purposively selected the top five firms in the world (see 1.1): Vestas from Denmark, Enercon and Siemens from Germany, Goldwind from China, and Suzlon from India.⁴ In addition, we included a specific Chinese private firm – Mingyang, ranked ninth globally – to provide diversity. These selected cases have sufficient heterogeneity (**Table 1**) to create a contrast between cases that ensure the internal validity of this research.

3.2 Patent analysis methods

As mentioned, we investigated the six cases through three sets of patent analyses. The first (3.2.1) and third (3.2.3) were based on key patent counts and categorisations and the second (3.2.2) used network-based methodologies to analyse patent citations. We used worldwide patent data for the international comparisons (see 3.3 for details) and adopted Derwent Classification with Manual Code (DCMC) to categorise the key technologies.

3.2.1 First set: the trajectories of key technologies

In recent years, patent analysis has been applied to analyse trajectories and key technologies (Ernst, 2003). For example, some researchers have attempted to use key patent data to map technological trajectories (Lee and Lee, 2013; Jeong and Yoon, 2014) and explore emerging trends (Ju and Sohn, 2014). Specifically, in the wind power industry, patent research has been conducted to study wind development at the sectoral level (Dubarić et al., 2011). In this study, we attempt to extend the above methods to study the trajectories of the key technologies (see 2.1) of leading wind turbine firms.

Following previous fieldwork and based on relevant concepts (Teece, 1986; Ju and Sohn, 2014; Phan and Daim, 2013), we used four dimensions to analyse key technologies through patents (also see 2.1): platform technologies, complementary technologies, emerging technologies and customised innovations (especially for innovation followers).⁵

⁴ Vestas is the flagship leading firm of the Danish wind energy sector. Since its foundation in 1981, it has worked closely with Risø National Laboratory (Denmark Technical University) on cutting-edge research. Enercon and Siemens (originally Danish) are Germany's most important and best-established wind energy firms. They have been operating for nearly 30 years (BWE 2012). Enercon's most significant platform innovation is the direct drive turbine, based on which they developed a series of leading-edge products (e.g. the 7.58MW E-126 turbine in 2007). Enercon's founder, Aloys Wobben, developed the world's first direct drive turbine in the early 1990s. Suzlon was founded in 1995 and remained the largest wind turbine manufacturer in India until 2013. China's Goldwind (founded in 1998) and Mingyang (founded in 2006) are both among the top three wind turbine firms and are listed on the stock exchange (Goldwind was listed in Hong Kong in 2008 and Mingyang was listed in New York in October 2010). In addition, Mingyang is the only non-state-owned enterprise among the top five Chinese wind turbine firms, which may lead to several idiosyncrasies in the case comparisons.

⁵ The major wind turbine technology categories include drive system, generator, control system, grid integration technologies (including wind farm management), tower construction and foundation, blade, etc. In this study, we only looked at those key technologies that have undergone dynamic changes in their technology trajectory over the past 20 years. For example, tower technologies have exhibited limited changes since the 1990s (and will have no significant change to offshore paradigms), and thus they were excluded. For better comparison, blade technologies were not studied because most of the sample firms had no such portfolios.

With the assistance of wind experts, we began by defining the **generator and drive system** technologies as the platform technologies of wind turbine firms, including gearless direct drive (DD) including permanent magnet direct drive (PMDD), and gear-based dual- or single-fed induction technology (DFIT/SFIT). In addition, the **grid connection and control system** was viewed as the key complementary technology in improving the reliability and quality of wind turbines. **Off-shore wind turbine** technology was recognised as the most important emerging technology because it is very different from onshore in terms of design, control, grid connection, etc. Finally, the customised innovation of wind turbine firms includes designs for niche markets, including *high-altitude*, *low wind speed*, *extreme temperature*, *sand-proof*, etc.

3.2.2 Second set: knowledge networks (knowledge flow and patenting collaborations)

Knowledge flow (learning and spillover). Knowledge networks are significant for knowledge flow (transfer) between firms. Recently, researchers have used patent citation-based methods to examine the knowledge networks for strategic analysis. Specifically, some have used the citation network indicators (e.g. centrality) to identify the key players (so called ‘nodes’) and their knowledge positions (Bekkers and Martinelli, 2012), measure knowledge flows between entities (Braun et al., 2010; Ju and Sohn, 2014; Li-Ying et al., 2013), and even indicate technological trends (Karvonen and Kassi, 2013).

Drawing on the existing approaches, we used patent citation network analysis to assess the importance of the technology attributes of our sample wind firms within the industrial network. In this study, the starting point was the knowledge network of wind turbine patents (4457 raw data, see 3.3). Because the patents are owned by the wind firms, we set up a network of cumulative patents at the company level (the top 15 firms plus Vensys and Aerodyn, see 4.2). The resulting network revealed an overview of patents and citation links in which the nodes represent key firms (their cumulative patents) and the links are the cumulative citations in-between. The literature has argued that the links can represent knowledge flows (between firms, excluding self-citations), if a patent cites another patent. We call the former a backward citation (citing) and the latter a forward citation (cited). In the figure, we set the size of the node to denote the number of patents owned by firms (i.e. the larger the node, the larger number of patents); in addition, the thickness of the lines (links) illustrates the intensity of the citations.

To study the knowledge network structure, we applied several indicators such as density, average distance, fragmentation, hybrid reciprocity and out- and in-degree centrality.⁶ This

⁶ Density is the sum of all of the values divided by the number of possible links. In this study, density is calculated by the number of patents for a specific firm (node) over the number of citations (links). The average distance is the average of the shortest distances between nodes that may explain the complexity of the network. In this study, it means the average shortest citation paths between key firms (nodes). Fragmentation is the proportion of firms (nodes) that cannot reach each other, like isolated islands. Reciprocity refers to the mutual links (citations) within the total links in the network. Degree centrality considers the number of links a node has, and because our network is directed, we distinguish between in- and out-degree centrality. In the context of our network of firms, the first indicates the number of forward citations (being cited) and the latter the number of backward citations (citing). The net citation count – forward citations minus backward citations – separates the net producers of knowledge from the net consumers.

allowed us to analyse the cohesion and centrality of the network while creating descriptive statistics for the entire network based on three indicators, as shown in **Table 3**. The network diagram based on the citation matrix between patent assignees analyses the position of a particular firm in each network. The network contains two types of companies: one is at the obvious core of the network (knowledge spillover as leaders) while the other is at the periphery (learners). The black circles indicate the (core) leading spillovers and the white squares indicate the peripheral learners. Analysing each company's network structure provides a better understanding of their roles within the network. We also used betweenness centrality to measure the degree of resources controlled by the core firms (see **Table 4**).

Patenting collaboration. R&D collaboration between entities can expedite the innovation process by providing diverse opportunities and ensuring that resources are used efficiently (Chesborough, 2003). Specifically, some recent research has explored specific sectors (e.g. nanotechnology, photovoltaic, etc.), arguing that R&D collaboration positively affects R&D output in terms of patenting (Luciano et al., 2013; Li et al., 2014). Following this, we used the co-patenting relationships to indicate the collaborative innovations. Based on the patent data of sample firms (see 3.3), we used data mining techniques to build the co-patenting matrix of relevant patent assignees, based on which we studied the co-patenting activities between the six firms and their collaborators in patenting.

3.2.3 Third set: globalisation intent

Limited studies have used patents to probe wind firms' globalisation efforts, particularly when firms may have strategic options regarding global competition with standardised innovative products (with considerable international patents) or competing in the domestic market by using customised technologies (with more domestic and limited international patents). Gosens and Lu (2014) made one of the few attempts to explore this issue in the wind sector, arguing that global intellectual property is critical for sustainable competitiveness in a global sense. Following this, we used the counts of the patent family (a series of patents taken in various countries to protect the prior basic patent) to understand the global market diffusion efforts of the leading wind firms. In general, more family patents indicated the firms' strategic intentions with regard to going global.

3.3 Patent data

We needed appropriate patent data to compare the international cases. The first and third analyses required a dataset that covered worldwide patent applications and patent families across different regimes. The second network-based analysis required another dataset that contained citation relations between these patents. Below, we briefly describe the patent databases and both datasets.

Following de Rassenfosse et al. (2013) and Nepelski and De Prato (2015), we used worldwide patent data (across various offices) to compare firms from developed and developing economies (see 4.4). We retrieved the worldwide patent data from the well-recognised Derwent World Patents Index (DWPI) and Derwent Patents Citation Index (DPCI) databases through the Thomson Innovation (TI) search engine. The DWPI and DPCI are integrated databases with patent and citation data from 50 patent-issuing authorities around

the world,⁷ rewritten by experts at Thomson Reuters for better interpretation, standardisation and error reduction. The DWPI and DPCI are viewed as better choices than other world patent databases in terms of comprehensiveness, accuracy and consistency across countries for both patent counts and citation data. In addition, the Derwent Classification with Manual Code (DCMC) system provides good data consistency across regimes and application-oriented codes.

Our first dataset for worldwide patent-counts was retrieved from the DWPI database for the analyses of trajectories (4.1) and globalisation (4.3). Overall, we searched the patent data of the six cases (see Annex D), with the patenting year (the priority year of submissions) during the 1993 to 2012 period (1993 was the earliest year of our patent records of the six cases). For **the first set of the analysis** (4.1), we used the basic patent applications for analysis as they were a better indicator of the original inventive activities. We only considered 'priority patent applications'; that is, to avoid double-counting all patent family members, only the first filing of the basic patent application was considered and all possible successive filings of the same invention to different patent offices were discounted. As a result, 2437 basic patents were collected for the 6 firms after the data cleaning process. For **the third set of the analysis** (4.3), we used patent family members instead, also drawn from the DWPI database. In this case, we searched 12605 patents for the 6 firms as family members in more than 20 countries.

The second dataset for **the global network analysis** (4.2) also used worldwide patent citation data, following Karvonen and Kassi (2013) and Bekkers and Martinelli (2012). Using citation data across different regimes was again to reduce the bias of using a single-office patent, especially when considering developing economies (see 4.4). We used the DPCI database because it was highly integrated and aligned with the DWPI database under the TI framework (data matching is more than 99.9% for the 6 cases), with the standardised patent data and classifications. The DPCI citation data also included citations from patent family members when eliminating the double-counts by TI experts. This was one of the most significant advantages of the DPCI, which was comprehensive yet with limited duplicates, especially compared with other citation databases (e.g. EPO Worldwide Patstat). In this study, we searched 4457 patent data records for a citations network (Annex B) containing 17 international firms, with 2435 for the 6 sample wind firms. Further, using the 2435 patents, we developed the collaboration networks (Figure 8) between the six sample firms and their collaborators (4.2).

4. Empirical analysis: trajectories, networks, and globalisation

In this section, we present the findings of our empirical analyses performed according to the methodologies discussed above. We begin with the analyses of the key technologies' trajectories and continue with the knowledge networks in terms of knowledge flow and collaboration before presenting the results of the globalisation patenting efforts.

⁷ National patent offices include the US Patent and Trademark Office (USPTO), the European Patent Office (EPO), China's State Intellectual Property Office (SIPO), etc. International patent offices include the World Intellectual Property Organisation (WIPO), which has international patents under the Patent Cooperation Treaty (PCT). In recent years, there have been worldwide patent databases that include patents from various offices for transnational patent studies, such as the DWPI and the DPCI, the EPO Worldwide Patent Statistical Database (PATSTAT), the Derwent Innovation Index (DII), the National Bureau of Economic Research (NBER), and the US patent citation databases, etc.

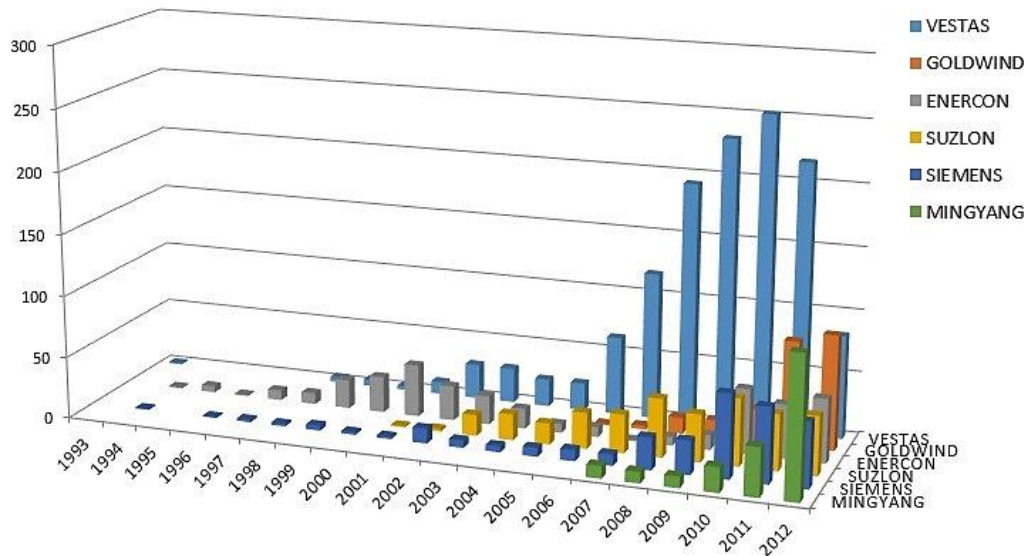


Figure 1 Patent submissions (basic) of the sample firms alongside growth

4.1 The trajectories of key technologies

Following the methods outlined in 3.2.1, in this section we use patent-counts to examine the trajectories of the key technologies of the sample wind turbine firms. From the DWPI database, we searched the basic patent applications of 2437 in numbers (3.3). Within this dataset, we further categorised the patents into platform technologies, emerging offshore technologies, complementary technologies and customised innovations through the data mining methods.⁸ We then collated all of the related patents (in Annex A) to generate the following figures.

Table 2 Patent citation information of the sample firms⁹

	Total patents				Top 10 cited patents	
	Total forward citations	Average forward citations	Total backward citations	Average backward citations	Total forward citations	Average forward citations

⁸ To mine the above data, we used an integrated method developed and validated by our team and patent searching experts (Thomson Reuters and China Academy of Science). This method combines a DCMC code-search and keyword-search, depicted as follows: (i) platform technologies: DCMC (X15-B01B generator and X15-B01A drive); (ii) complementary technologies: DCMC (X15-B05 control) and keyword 'grid'; (iii) emerging technologies: DCMC (X15-B05 offshore); (iv) customised innovations: keywords, e.g. high altitude, etc. We read some patents to test false positives as the simple validation, together with the domain experts. This method performs well in categorising most patents, except those peculiar patents that fall into two or more categories (such as a generator's control technology) – in which case we count the patents in both categories. More advanced data mining methods may be needed for patent categorisation in future research, such as subject-action-object (SAO) semantic methods.

⁹ For most of the M&A cases, we did not include the target firms' patents to acquirers, either because they were not clearly significant (e.g. Flender to Siemens, Hansen to Suzlon, etc.), or the acquirers had no exclusive rights on the target firms (e.g. Goldwind and Vensys). For Suzlon, we provided the patent discussion on both 'Suzlon only' and 'Suzlon+Repower'. However, in some circumstances due to data complexity (see 4.2, knowledge network part), we only retained the acquirers in the network when cleaning patent assignees by combining the M&A parties (e.g. Repowers' patents to Suzlon).

Goldwind	33	0.14	107	0.46	20	2.0
Mingyang	43	0.21	92	0.46	24	2.4
Suzlon	75	1.23	213	3.49	43	4.3
Suzlon&Rep ower	1195	3.84	1292	4.15	297	29.7
Enercon	1952	5.76	1616	4.76	503	50.3
Vestas	4001	3.77	5479	5.16	592	59.2
Siemens	1059	3.48	1875	6.16	420	42.0

From **Figure 1**, we can argue that Vestas, Enercon and Siemens have been leading in terms of patent submissions since the 1990s whereas Suzlon, Goldwind and Mingyang have been catching up rapidly in recent years. However, considering the quality of the patents using citations (**Table 2**), Asian firms are currently falling far behind the European leaders. For example, Vestas' top-cited patents each have 59.2 forward citations on average, which is almost 30 times that of Goldwind's patents. In addition, from these top-cited patents' information, European firms appear to have wider portfolios of key technologies, as their top-ten cited patents involve broad domains ranging from wind turbine generators and rotor blades to wind power systems and installation methods. In contrast, Asian firms' top-ten cited patents are mainly limited to minor turbine design improvements.

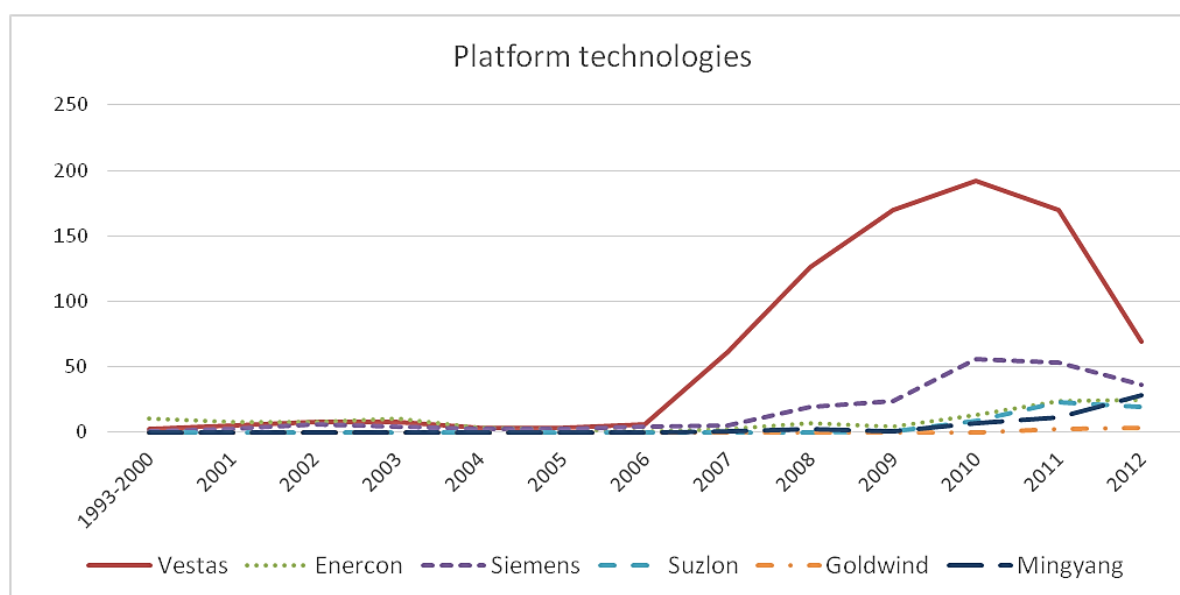


Figure 2 The patent counts of platform technologies in the six leading firms

Platform technologies. As mentioned in 2.1, there are two major platforms: gear-based dual- or single-fed induction (DFIT/SFIT) and gearless direct drive (DD) technology. Enercon and Goldwind follow the DD pathway whereas Vestas, Siemens, Suzlon and Mingyang use gear-based systems like DFIT. From Figure 2, we can see that DFIT remains dominant from a patent view, with Vestas leading (823 patents on DFIT) and newcomers such as Suzlon and Mingyang actively joining in since the late 2000s. Thus far, there has been no sign that DFIT will face threats of being disrupted, as it still accounts for the majority of the existing patent pool. In contrast, the patent submissions for DD have been led by Enercon since the late 1990s with 117 highly-cited patents, although the others have begun to catch up, especially after Goldwind participated in 2008. However, this does not show any sign of a convergence of two existing platforms. From a patent knowledge perspective, we argue that

these two dominant designs may co-exist for some time into the future, which enriches the observations from market data in 2.1.

Despite the differences in design, the European firms are leading in terms of the patented platforms, with more patents and higher citations; in addition, they have higher portfolios of drive/generator technologies among all of their patents (calculated from Annex A). However, Asian leading firms are catching up quickly. Chinese firms have been striving to develop indigenous platform technologies since 2006, in both PMDD (Goldwind, acquired from Vensys) and DFIT (Mingyang, acquired from Aerodyn), regarding firm-level preferences. The invention patents of Goldwind and Mingyang related to platform technologies outnumbered those of Enercon in 2011 and 2012, respectively (Annex A), and these platforms have enabled the Chinese leading firms to keep on track for incremental innovations in the following years.¹⁰ This is a sign that the Chinese wind firms are starting to challenge the existing leaders of the current trajectory, leveraging their capacity for manufacturing innovation, similar to Huawei in the telecom sector or Lenovo in the personal computer sector. In contrast, Suzlon (without Repower) has limited patents with regard to platform technology, which echoes the fact that they only started to use DFIT in their recent product (S9x). However, Suzlon was greatly strengthened by Repower's patents after the acquisition in 2007.

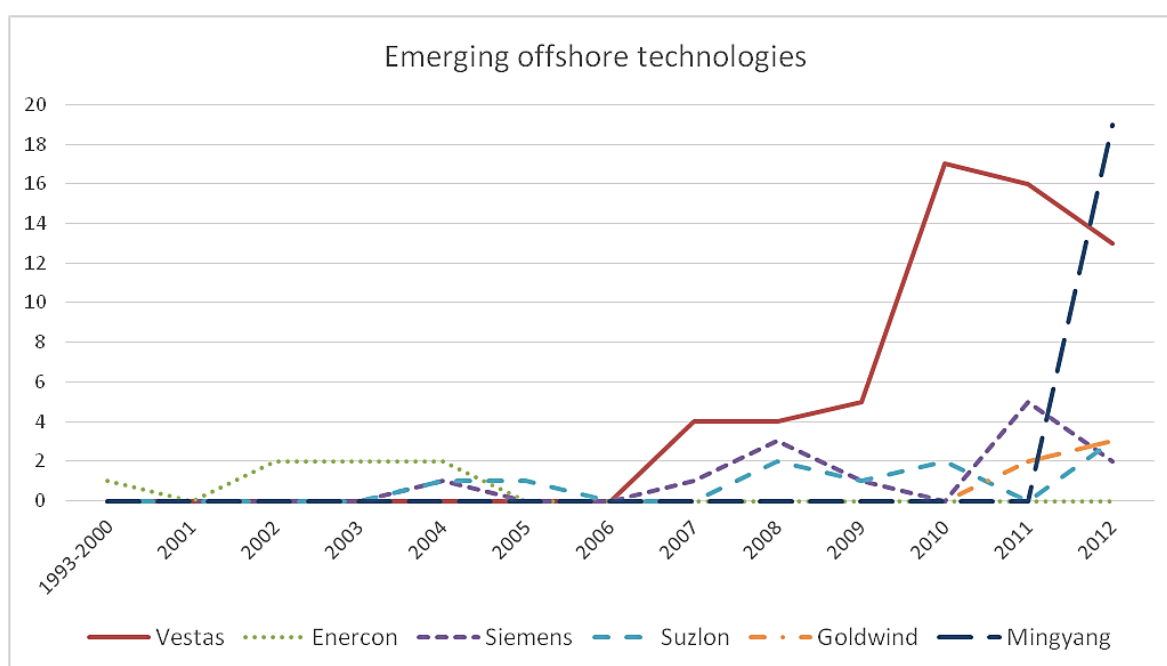


Figure 3 The patent counts of emerging offshore technologies in six leading firms

Emerging offshore technologies. Asia's leading firms have paid close attention to catching up with the existing platform technologies, but they may have neglected the

¹⁰ In China, there are three patent categories: invention patents, utility models, and designs. For platform and key complementary technologies, we were advised by patent experts to use invention patents as the indicator of core innovations of Chinese wind turbine firms, including Goldwind and Mingyang. We can see that these invention patents only accounted for a third to a half of the total patents of Chinese firms. For Goldwind, out of their 231 patents, 93 were invention patents. This may partially indicate the 'patent tsunami' issue in China, as the real value of many patents is somehow dubious.

emerging offshore knowledge until very recently (Figure 3). Goldwind had no offshore patents until 2011 while Mingyang only started offshore patents in 2012 (although with a sudden burst of 19 submissions). Suzlon has also been incompetent in this field, although Repower can compensate for this. In contrast, European leading firms started much earlier. Enercon is also one of the leaders in offshore technologies. Its patent submissions for offshore turbines date back to 2001, making it the earliest entrant worldwide. Vestas and Siemens followed soon after, as they started patenting offshore technologies in 2003, and Vestas owns the largest number of patents among these firms. This fact provides a contrast to the narrative that Chinese leading firms are significantly focusing on offshore technologies, and are challenging their European counterparts in this aspect. From the patent perspective, Asian leading firms are paying less attention to offshore knowledge compared to the existing platform designs, and are falling far behind after a very late start. European leading firms, however, have acted as innovation leaders and first movers in this new technological trajectory.

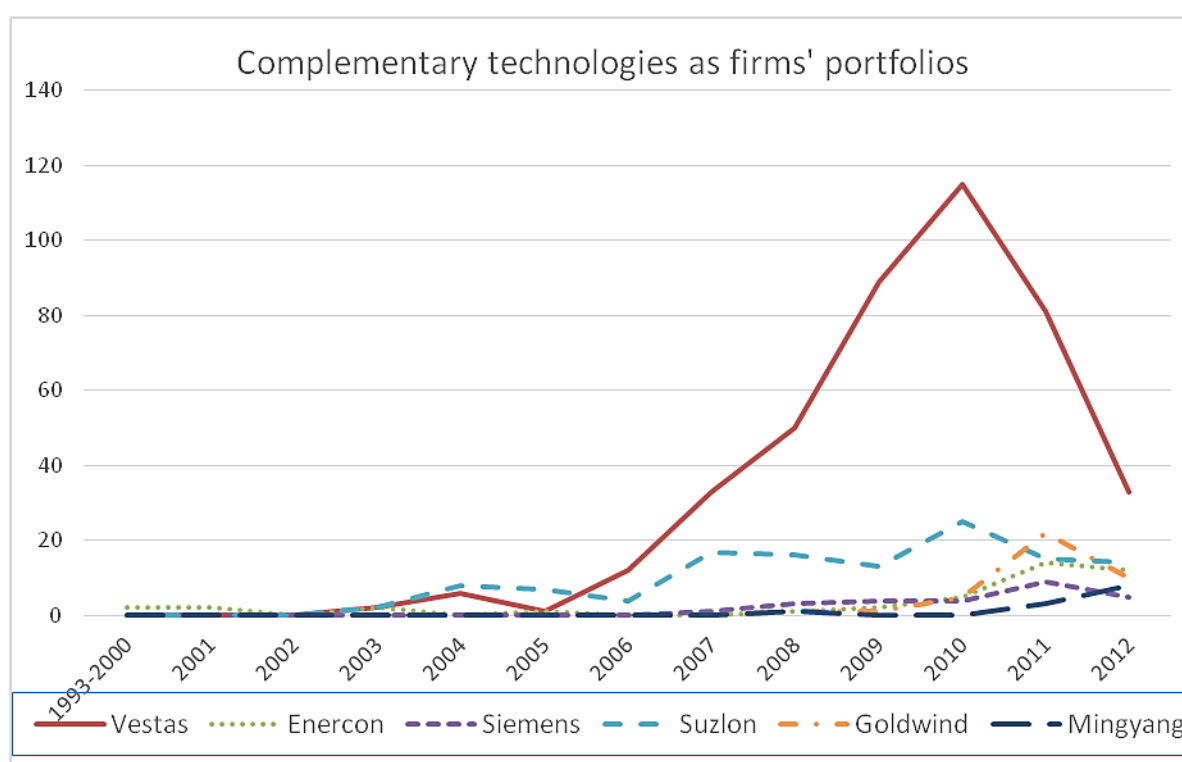


Figure 4 The patent counts of complementary technologies as firms' portfolios

Complementary technologies as firms' portfolios. Complementary technologies are essential to firms' competitiveness in profiting from innovation (Teece, 1986; Zhou et al., 2015). However, several recent inquiries have maintained that the significance of complementary technologies (as portfolios) to firms may vary and depend on the sectorial and firms' characteristics; specifically, high-technology firms may enhance their performance by having diversified portfolios while low-technology firms cannot (Lin et al., 2006; Lichtenthaler, 2010). When we extended this argument to the wind turbine industry, we realised that European leading firms are continuously emphasising portfolio-complementary technologies (control and grid-connection) for reliability and quality from a patent perspective – from Annex A, they have a higher portfolio rate of complementary technologies compared with their Asian counterparts.

As Figure 4 shows, Vestas, Enercon, and Siemens have all exhibited strong interest by filing patents in these aspects since the 1990s. The Repower side of Suzlon has also demonstrated a strong patent knowledge base since the early 2000s. In contrast, Asian leading firms may have problems in this regard. For example, only after 2011 did both Goldwind and Mingyang start to file patents for complementary technologies. Suzlon, without Repower, owned very limited relevant patents by the end of 2012. This opposes the argument that Asian leading firms are on par with the European leaders in terms of knowledge position. In fact, Asian leading firms must devote more effort to enhancing their complementary technologies. This may also explain the ‘curtains’ in China that are partially due to the less reliable grid-connection and control technologies of domestic turbines. It also adds empirical evidence about the wind sector to the literature on how high-technology firms more successfully consider diversified portfolios.

Finally, Annex A shows that Asian leading firms have advantages thanks to customised innovations, yet due to the small numbers, we do not present the figure. Based on the analysis, we argue that European leading firms are still leading from a patented knowledge perspective, in terms of platform trajectories, emerging offshore technologies, and portfolios for reliable and quality products. Some Asian leading firms have developed their indigenous platforms so that they are able to challenge the existing leaders; however, when considering other technological aspects, Asian leading firms are still rather weak despite their mere edge on customised products. In addition, they put less emphasis on platform/complementary technologies in terms of percentage of patents at the firm-level. This is in contrast to the perception that Chinese and Indian firms are growing significantly and have come to account for a large share of the global wind market since 2007. Based on this contrast, we argue that Asian leading firms may have inferior knowledge competence for creating new trajectories, but may have successfully used other strategies for competitions (Zhou and Minshall, 2014), such as low-cost manufacturing, agile followers’ strategy, or customised designs for domestic market occupation.

4.2 Knowledge networks: knowledge flow and collaboration

Knowledge flow (learning and spillover). Following the methods outlined in 3.2.2, we created the knowledge network for wind turbine patents (Figures 5-7) based on the mining of patents and citation data and using the visualisation software UCINET. To develop a better overview, we included all of the patents of the top 15 global wind turbine firms and two key design firms (Vensys and Aerodyn) that were significantly involved in knowledge transfer to Asia’s leading firms. Based on 4.1, we divided the period (1993-2012) into two phases, making 2006 the cut-off year, to construct two sub-networks (1993-2006 and 2007-2012) and a full network (1993-2012). This allowed us to research the firms’ growth changes over time. For detailed data about the citations and the frequency statistics of the three networks, refer to Annexes B and C.

Table 3 Changes in the knowledge network: descriptive comparative data

Indicators\Time	1993-2006 network	2007-2012 network	Full-time network
Density (containing self-citations)	19.6758	12.2872	29.5121
Density (excluding self-	17.9792	10.8162	26.511

citations)			
Average distance	1.153	1.485	1.441
Fragmentation	0.423	0.225	0.206
Hybrid reciprocity (percentage of reciprocated total links)	0.4767	0.4808	0.4775
Out-degree centrality	0.22671	0.17632	0.20337
In-degree centrality	0.13248	0.15408	0.15192

Table 3 shows the evolution of the network structure's key indicators for the different periods. We investigated the density and cohesiveness (e.g., average distance, isolated point and reciprocity) of the network that grows over time (see 3.2.2). From these data, we discovered some interesting features. For example, the decrease in network density (total patents/total citations) may mean that patent citations between firms grew exponentially after 2007, given that the total number of patents is also increasing, as knowledge flows (citations) appear to expedite within the network. In addition, the decrease in fragmentation (proportion of firms/nodes that cannot reach each other) shows that there are fewer and fewer isolated islands within the wind knowledge network. The reciprocity has remained stable, which may denote that the producers and consumers of knowledge have not changed significantly over time in the wind turbine industry, as innovation leaders are still spilling over knowledge and latecomers are still learning and absorbing. There is no clear sign of leapfrogging by latecomers in terms of knowledge.¹¹ The centrality degree measures the number of links (citations) that a node (firm) has. The decreasing out-degree and increasing in-degree centrality (**Table 3**) may indicate that more companies' patents were less highly cited, and while there is no sign of emerging dominant leaders, there is still fierce knowledge competition in the wind industry, which has not yet matured and stabilised.

¹¹ The increase in the average distance may mean that the knowledge network becomes more complex, and that more key players become involved in knowledge production and consumption, respectively. This may indicate that more Asian firms are coming in as knowledge consumers, or that more European design firms are producing more knowledge to transfer to Asia's leading firms.

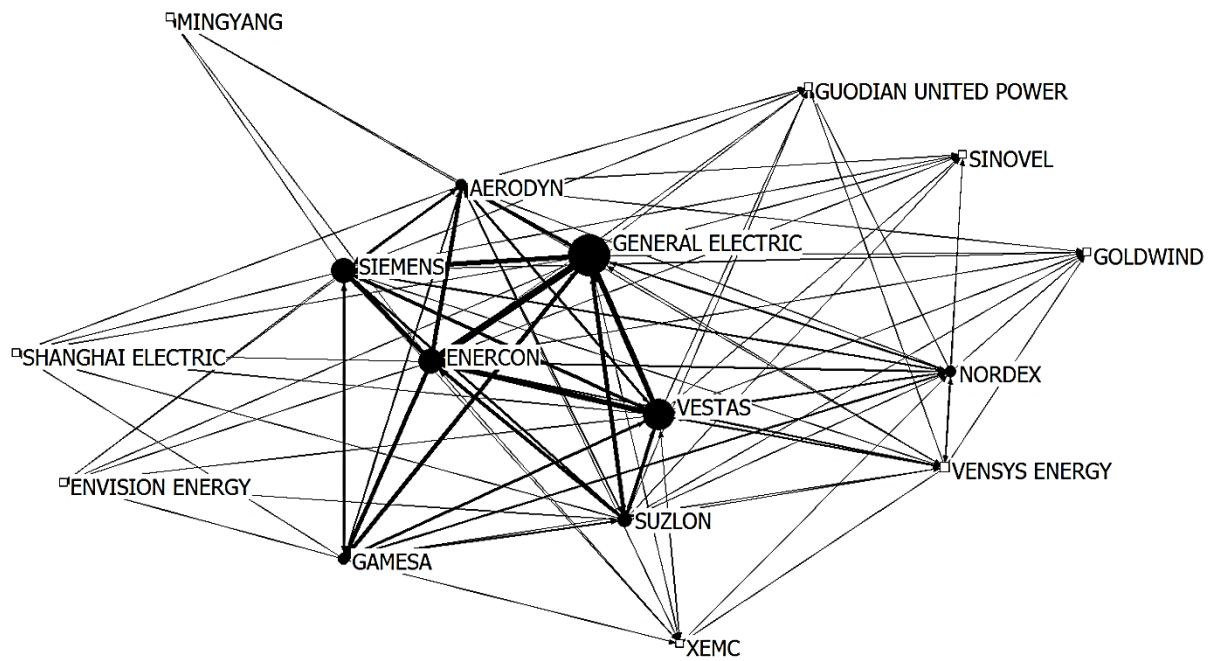


Figure 5 Firms' network 1993-2006

Figures 5-7 illustrate the resulting network of wind firms. The lines represent the cumulative citations in both directions; the thicker the line, the more citations between the two firms. The size of the nodes is determined by the number of self-citations. The core/periphery structure of the three network diagrams represents each company's position in the network. As mentioned in 3.2, the black circles represent the companies in the **core** position, while the white squares indicate firms at the **periphery** of the network (less important). Through the algorithms (UCINET software), the core/peripheral positions are determined by the thickness of the links (citations) and their distance from the other nodes (paths). Firms with higher citations and shorter paths are positioned at the centre and defined as **core** positions.

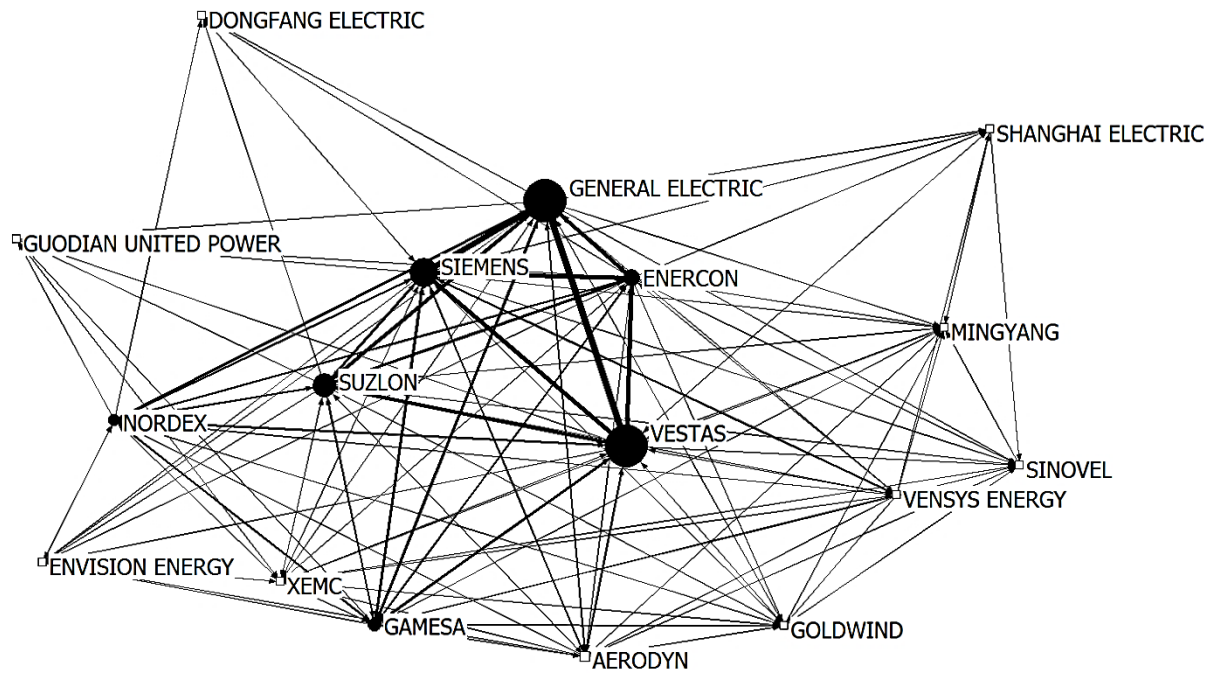


Figure 6 Firms' network 2007-2012

First, we observed that the core companies (black circles) in all three networks included traditional European leading companies such as Vestas, Siemens, Enercon, etc. Suzlon (with Repower) also appeared to be a core firm, which may be attributed to Repower's rich knowledge base. Design firms such as Aerodyn also appeared in the earlier network (1993-2006) and the full one, suggesting that they also played significant roles in knowledge flow. In contrast, the Chinese firms were all at the periphery, even in the later network (2007-2012), which may indicate that they have yet to play a key role in knowledge flows. Second, the circles representing the companies in the core positions were generally larger (more self-citations), indicating that they depended considerably on their own in-house knowledge. From 4.1, we know that these European firms had larger patent portfolios, which may explain why they frequently self-cited. This may be a unique phenomenon associated with the wind turbine sector (high-technology and still young). Third, the network figures also revealed that those firms in core positions were closer to each other, suggesting that similar nodes were closer. Thus, we argue that European leading firms were similar to each other due to knowledge spillover (Suzlon benefits from Repower), whereas the Chinese firms were clearly the learners.

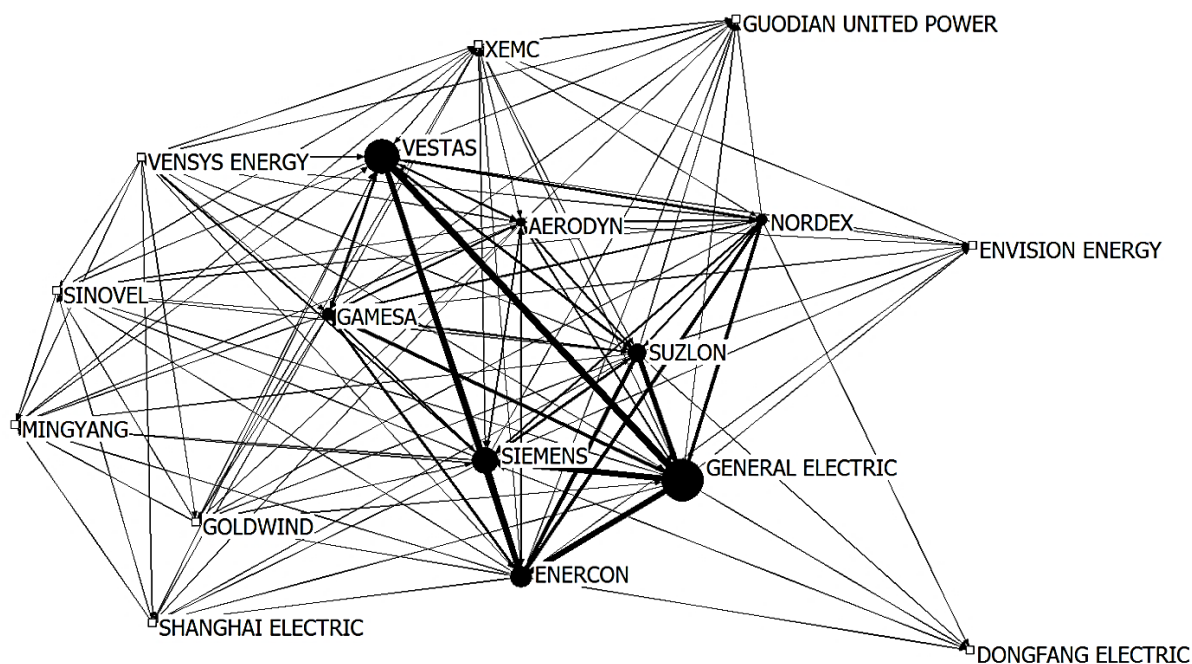


Figure 7 Firms' network, full time period 1993-2012

Table 4 shows the key indicators for the 17 firms, in 1993-2006 and 2007-2012, respectively. The citation net count indicates the net knowledge producers (positive) and net knowledge consumers (negative). Enercon, in this case, contributed significantly to the world, with by far the highest number of net citation counts. In addition, the design firms, Aerodyn and Vensys, also acted as net knowledge producers, with high positive net counts. In contrast, many of the core firms (such as Vestas, Siemens, and Suzlon) were net consumers but had a high number of both backward (out-degree) and forward (in-degree) citations, which meant that they were very active in knowledge flows, and engaged in spillover knowledge on a considerable scale while also absorbing knowledge (a good open innovation model). The Chinese leading firms played a very limited role in the knowledge network, as they had a very limited presence in terms of both citing and being cited (Goldwind had the highest out-degree and had only been cited eight times). Thus, they were still mainly the learners (knowledge consumers) in recent years.¹² The betweenness centrality, which indicates the control of resources and positions in the knowledge network, also echoes the above observations.

Table 4 Centrality indicators for the 17 firms (including our 6 sample firms)

Firm/indicators	1993-2006				2007-2012			
	Betweenness	Out-degree centrality	In-degree centrality	Net citations	Betweenness	Out-degree centrality	In-degree centrality	Net citations
ENERCON	2.531	1087	325	762	6.123	535	155	380
VESTAS	2.763	615	727	-112	26.825	441	658	-217
SIEMENS	4.346	563	635	-72	24.123	301	607	-306

¹² XEMC was an abnormal outlier here, and thus will require more investigation in future studies.

SUZLON	2.181	269	645	-376	4.434	327	340	-13
GE	4.346	972	695	277	9.123	728	446	282
GAMESA	0.905	159	467	-308	2.634	279	202	77
NORDEX	1.208	169	474	-305	9.303	127	240	-113
AERODYN	4.346	374	77	297	1.277	106	46	60
VENSYS	0.375	101	22	79	1.401	51	13	38
XEMC	0	7	81	-74	44.404	23	50	-27
GLODWIN D	0	0	28	-28	0.451	8	25	-17
SHANGHA I	0	0	21	-21	0.111	6	10	-4
MINGYAN G	0	0	12	-12	1.336	4	38	-34
ENVISION	2.531	0	24	-24	0.011	2	40	-38
SINOVEL	0	0	52	-52	0.458	2	40	-38
DONGFAN G	0	0	0	0	0	1	5	-4
GUODIAN UNITED	0	0	0	0	0	0	31	-31

The analysis, which distinguished between true innovators and catch-up learners in different periods (1993-2006 and 2007-2012), offered some interesting insights echoing the qualitative narratives (section 2) with quantities estimations or providing contrast. In this case, European leading firms were still leading in the knowledge networks and behaved as knowledge producers. Enercon was still a (distinguished) net knowledge producer while Vestas and Siemens remained active in knowledge inflow and outflow. Chinese leading firms, despite their remarkable market success, were still far from being significant in this knowledge network; however, they began participating in knowledge production (though still limited as forward citations) in the 2007-2012 period. Suzlon, however, successfully grew from a net knowledge consumer (net citations -376 in 1993-2006) into an ambidextrous innovator (-13 in 2007-2012), which may be attributed to its successful integration of Repower.¹³

Patenting collaborations. In this study, we developed a co-patenting matrix (Annex D) to create patenting collaboration networks (**Figure 8**) for six leading firms and between other collaborators, following the method/data in section 3. From **Figure 8**, we can tell that there was limited joint-patenting collaboration between these leading firms, which may be the rationale in high-technology industries in an open innovation era. The leading firms were competitors, and thus were more comfortable collaborating with patenting partners within specific ecosystems (e.g. universities) or value chains (e.g. component suppliers or project developers, as mentioned in section 2). From the figure, we can see that Vestas and

¹³ Some experts have opposed this argument, claiming that Suzlon acquired Repower but had limited integration. For example, Repower's staff mentioned that Suzlon does not have access to Repower's patents, although these may officially belong to Suzlon (in 2010-2014). In 2015, Suzlon sold Repower, and the latter is called Servion now. Others have argued that in most cases the Repower side produced the most valuable patents, based on which Indian teams developed mainly niche customised innovations.

4.3 Globalisation intentions

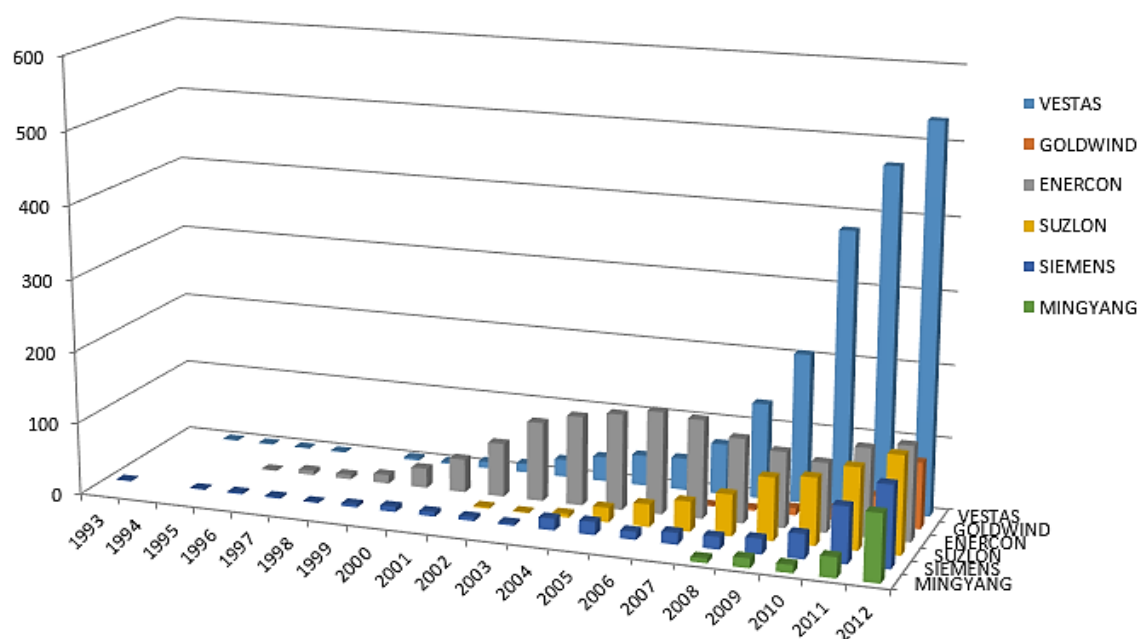


Figure 9 International patents: patent family counts

Following 3.2.3, we searched for the patent families of the sample firms. The findings are shown in **Figure 9** and **Figure 10**, which show that the Chinese leading firms were still rather domestic from a knowledge perspective, as they mainly filed patents in the domestic markets (99%). For example, Goldwind had only one international patent while Mingyang had three by the end of 2012. We argue that Chinese firms may face difficulties when developing global products and competing in the global market with regard to technological competitiveness. This phenomenon contradicts the narratives (based on qualitative interviews) that Chinese leading firms such as Goldwind and Mingyang have strong ambitions to achieve a global reach in terms of not only the market but also technology leadership. It seems that their collaboration with Vensys and Aerodyn mainly helped them to file domestic patents. However, it does support the existing arguments that the globalisation of Chinese wind turbines is leveraging lower costs (or higher cost/performance) and other non-intellectual resources such as financial loans.

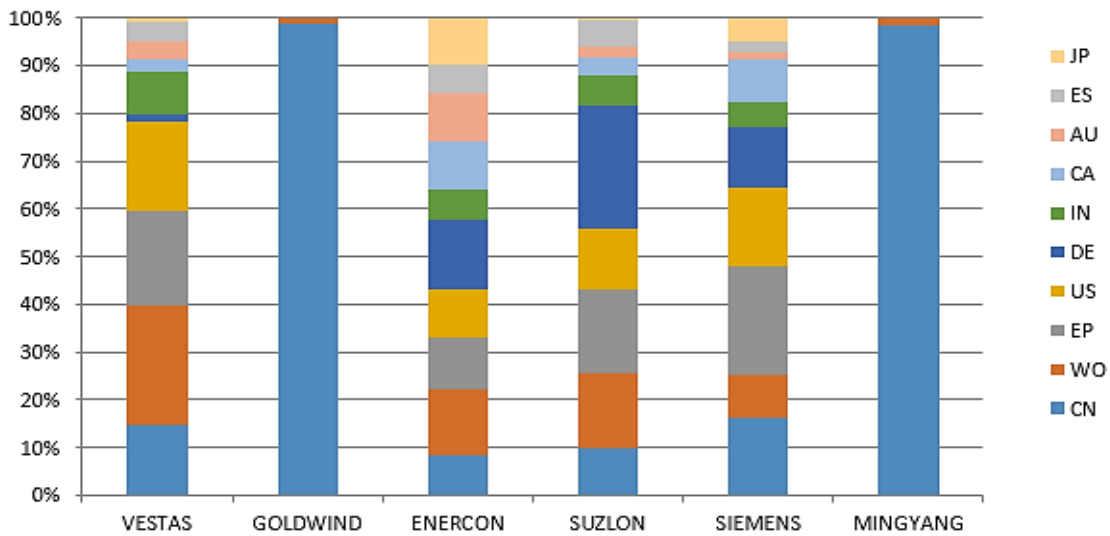


Figure 10 International patents: patent families in percentages

In contrast, Indian firms are culturally closer to Western firms, and thus may be better able to integrate global innovation networks. For example, Suzlon (with Repower) was far more active in terms of filing international patents than its Chinese counterparts (**Figure 10**). Similarly, the European leading firms were all very active in submitting international patents in diverse markets. For example, Vestas had 5093 international filings (patent family) in more than 20 countries based on 1061 basic patents. Enercon, in particular, emphasised international patents with more than 4000 international filings (patent family) in more than 20 countries based on 337 base patents, possibly due to their aggressive globalisation strategies. They had the most international patent submissions and the highest rate of family patents in different countries (**Figure 10**). This may indicate that Enercon devoted more effort to international market exploitation than to R&D exploration (as indicated by the basic patents) in recent years. This finding echoes the previous narratives that European leading firms have set out to become multi-national firms.

4.4 Validity of analysis and methodological limitations

To validate the above findings, we conducted follow-up interviews with wind experts (incl. China Wind Energy Association, Dr Qin Haiyan, etc.). Most of the interviewees had no objection to the analyses on platform/complementary/customised technologies; specifically, some expressed concern for China's offshore and argued that it may be worse than patent results. We also checked for the international knowledge flow, and many maintained that the patent results seemed to be consistent (in principle) with their field knowledge. However, some raised concerns regarding patent data bias (e.g. overheated Chinese patent filing) that must be handled carefully.

Table 5 Comparison of analyses with data descriptions

Analyses	Data sources	Patent data types	Patent/citation value	Geographic bias	Institutional bias
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First set (4.1)	DWPI	Worldwide basic patent	Varying	Low	Medium
Second set (4.2)	DPCI	Worldwide citation	Varying	Low	Medium
Third set (4.3)	DWPI	Worldwide family members	Varying	Low	Medium to low
Other single-office data-based studies	USPTO as an example	Single-office basic patent/citation	Medium to high	High	Low

Thus, we collated the possible data bias that might influence our analysis (**Table 5**). Following de Rassenfosse et al. (2013) and Frietsch and Schmoch (2010), transnational patent analysis may have issues such as uneven patent values, geographic bias and institutional bias. We argue that such data bias, despite leaving much room for improvement in future studies, did not cause significant distortion of the results.

First, in the analysis of key technologies (4.1), we used worldwide patent counts to reduce the **geographic bias** caused by the propensity to file patents in local offices, which is more obvious in developing economies (e.g. Chinese firms usually have the most filings in SIPO). Single-office (e.g. USPTO, EPO, etc.) data are subject to geographic bias and the international patent (PCT) count may mask the local nature of inventive activities. The worldwide patent data, by contrast, can better capture these dimensions, especially when covering both developing and developed countries. However, this global coverage eliminates the geographic bias while raising the **institutional bias** due to the peculiarities of individual patent systems, as the patent values are uneven across regimes so that simple counts may cause bias.¹⁵ These biases can be partially reduced by using basic (priority) patent counts (3.3) to reduce double-counts of all applications. Moreover, advised by industrial experts, we used invention patent counts (higher value compared to other patents) to reduce bias when examining Chinese firms' platform technologies (4.1). Using patent value conversion rates can fairly alleviate bias (de Rassenfosse et al., 2013); however, due to length limits this method will be left to future studies.

Second, for the globalisation analysis (4.3), although counting patent family members may have institutional bias in evaluating inventive activities, it can effectively indicate the global diffusion of a single invention across different regimes. In this sense, we argue that the **inconsistency of patent value** (e.g. as a rule of thumb, three patents in Japan are equivalent to one at the EPO) does not significantly affect the observation of globalisation trends by tracing family members.

Third, for the knowledge network analysis (4.2), we used transnational patent citation data following some existing studies (3.3). As **Table 5** shows, single-office citation data can create **geographic bias** that may affect validity; specifically, Goldwind only had two patent applications (out of 233 in total) outside China. If we used the USPTO or PCT data in this

¹⁵ There are many causes of institutional bias: for example, some patent systems have tight control on the scope of applications that encourage many narrow patents (e.g. Japan) while others have less rigorous examinations that attract a great number of filings (e.g. China). In addition, different offices have different categories of patents (e.g. utility model and design in China, software and continuations at USPTO) that may cause bias.

case then the relevant citation data would have suffered severe bias (citations of 2 vs. 233). However, this created *institutional bias* due to the different regulatory requirements of patent offices. For example, for USPTO it is mandatory to cite all previous arts by applicants, whereas for EPO the citations are made by examiners. In addition, China's patent office only requires mandatory citation after 2005 and examination of all global previous arts after 2009. Thus, in China, the backward citations may be less than expected before 2009 due to lack of jurisdictional enforcement. For example, Goldwind had only three patents that cited Vensys until 2012. Due to cultural and language gaps, the patents in developing countries are less cited by those in developed economies. However, these institutional biases have been reduced for the data after 2009, with the development of jurisdiction (e.g. China with international standards). However, the use of a professional database can also help reduce the abovementioned institutional bias. The DPCI has integrated missing citation data that are not disclosed in the public SIPO database, and it provides an expert-translated platform so that non-English patents can be understood. A data bias also exists for co-patenting analysis. Not all collaborations can lead to the co-filing of patents; in many cases, collaborators negotiate licensing terms in advance and then only one of partners files the patent in practice.

5. Discussion and conclusions

In this study, we conducted an empirical comparison of the patent knowledge bases of global wind turbine firms in Asia and Europe. We used a set of patent-based methods to analyse the specific wind turbine firms in terms of the trajectories of key technologies, knowledge networks and globalisation intentions. We believe that integrating these patent methods allows for a robust assessment of firms' knowledge competitiveness. Using quantitative methods, our systematic analyses generated interesting insights that partly provide surprising contrasts to the conventional wisdom about wind technology development and partly empirically validate some prior arguments (see Section 2). Our main conclusions are as follows.

First, by examining the firms' patent trajectories of key technologies over time, we revealed the differences in the knowledge profiles between these leading firms. In addition to the firms' specifics, we argue that European leading firms have similar knowledge profiles over time to the global leaders, whereas the Asian ones are more similar to each other, as followers. Although the two existing wind turbine technology platforms (DFIT and DD) co-exist as the core of the sectoral trajectories, the analyses of knowledge bases show no signs that Asian leading firms will create new paradigms that may disrupt the existing ones. From the patent perspective, we argue that European leading firms continue to lead with regard to the existing trajectories, in terms of platforms and portfolios for reliable and quality products. They are also first-movers in the emerging offshore technologies, which means they may also lead the next-generation technologies. However, some Asian leading firms have developed proprietary platforms within existing paradigms. These platforms allow them to challenge the technological leaders by leveraging cost-performance capabilities and customising innovations for domestic needs. This may explain why Chinese and Indian firms have enjoyed considerable market success in recent years.

Second, the patent analysis of wind knowledge networks and network activities (transfer and collaboration) revealed the innovator-follower dynamics in the sector. Specifically, we found that European leading firms are far more active within the knowledge flow activities as

knowledge spillovers (producers) than their Asian counterparts. In addition, we found that some European firms are even net knowledge producers (e.g. Enercon), whereas others are active in terms of both knowledge inflow and outflow (e.g. Vestas, Siemens). Suzlon benefits from their ties with Repower. Chinese firms, however, are weak in terms of knowledge outflow, but demonstrate strong learning capacities (knowledge inflow), which echoes the narratives and earlier findings about their endeavours over indigenous platforms. European leading firms engage in much more patenting collaboration with their value chain partners, whereas Asian leading firms are still adopting the traditional in-house R&D approach with limited patenting collaboration (including collaboration with international partners such as Aerodyn and Vensys).

Third, our analysis of international patents (patent family) revealed the globalisation attempts of lead firms. Chinese leading firms, despite the ambitious globalisation strategies, have limited knowledge resources for global technology competition. This supports the argument that Chinese firms are not primarily leveraging broad research-based knowledge resources, but other resources such as capabilities for rapid catching up, producing heavy-industry products at scale and driving down cost. The European leading firms and Suzlon have better intellectual property portfolios for addressing diverse markets.

Based on these patent analyses, we argue that Asian leading wind firms have less developed knowledge bases, which limits their chance of leapfrogging to new technological paradigms in the near future. However, regarding the existing trajectories, Asian leading firms are catching up very rapidly on both indigenous platforms and in terms of market shares. When leveraging specific resources and business strategies, they have a chance to challenge the global leaders on the existing trajectory, or may even duplicate the catch-up successes achieved by Chinese Huawei or Lenovo in the information and communication technology (ICT) industry.

This study also produced further insights into the dynamics of the wind turbine sector. For example, the knowledge network analysis suggests that the wind sector is still young and relatively fragmented. The comparison of knowledge networks showed increasing fragmentation and increasing distance. This differs from other sectors, such as the ICT industry which is characterised by increasing density and decreasing distance (Bekkers and Martinelli, 2012) -- it seems that leading wind turbine firms (e.g. Vestas, Enercon, etc.) are much less dominant in this network, unlike Cisco and Huawei in the ICT sector. In addition, compared to the ICT sector there is less open innovation among wind industrial leaders, and wind firms tend to collaborate first and foremost with value chain partners. Leading wind firms (especially the European leaders) emphasise technology portfolios. These findings align with research which shows that high-technology firms have diversified portfolios that may increase their R&D outputs whereas low-technology firms need a more strategic focus (Lichtenthaler, 2010).

The above findings may offer important implications for systematic and nuanced policies (Quitow et al., 2014). European players have successfully developed the dominant designs based on the long-term supply-side policies in renewable energy innovations, along with the regulatory incentives for the policy-driven leading market. However, they are facing challenges as the onshore wind technologies mature; in this case, cost-reduction and technology robustness can threaten the first-movers' advantages, creating opportunities for those trying to catch up. European governments need to create new lead markets for the

next generation of wind technologies (e.g. offshore) to ensure their leadership positions. Asian governments may need to modify policy frameworks for better catch-up strategies, such as balancing the hiking market and lagged indigenous R&D, encouraging open innovation and collaboration for technology exploration, and reframing the globalisation policies. First, the Asian governments need to recognise that encouraging market booms but neglecting the supply of key technologies may jeopardise Asia's opportunity in the long run. In addition, participation in global knowledge networks and collaboration need to be combined with strengthening of Asian national innovation system (Urban et al., 2012).

Limitations do exist. First, patent analysis methods must take care in reducing the data bias in future research (see 4.4). In addition, single patent indicators may cause false results due to data bias, so future research may consider using integrated indicators. In addition, advanced text mining methods for patent categorisation should also be explored in future research (e.g. avoiding double-counts for technologies that fall into two or more categories). Methodology-wise, patent data can provide quantitative estimations in general, and may help to find aggregate phenomena that qualitative inquiry cannot detect or may overlook. However, for some specific cases, the use of patent indicators may require assistance. For example, Enercon's innovation competence might be underestimated if we only consider patents (see 4.2) whereas through interviews with domain experts, Enercon's decline in terms of patents may also be attributed to their specific strategy of being low-profile to protect their business secrets. In addition, patents can only explain explicit knowledge bases, but might have difficulty deciphering other tacit capabilities, especially for those trying to catch up. For example, some Chinese firms have limited patents but can learn very quickly by adopting various measures and achieve market success by leveraging other competitive edges. Despite the significant value of patent data, we argue that this patent analysis might be complemented by qualitative enquiries for a better overview, as in Lema et al. (2014), Dai et al. (2014), and Narain et al. (2014). This may also indicate a fruitful direction for our future research. We may consider integrating patent methods and qualitative interviews to improve our research validity.

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Annex A: Summary of patent counts for sample wind firms

Year Patents		1993-2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Goldwind	Total	0	0	0	0	0	0	1	3	13	14	27	84	92
	PMDD	0	0	0	0	0	0	0	1	1	4	15	36	39
	PMDD (invention)	0	0	0	0	0	0	0	0	0	1	9	23	19
	Grid/control	0	0	0	0	0	0	0	0	3	1	6	29	13
	Grid/control (invention)	0	0	0	0	0	0	0	0	1	1	5	22	10
	Offshore	0	0	0	0	0	0	0	0	0	0	0	2	3
	Customized	0	0	0	0	0	0	0	0	0	1	3	0	0
Mingyang	Total	0	0	0	0	0	0	0	10	9	9	20	39	113
	DFIT	0	0	0	0	0	0	0	2	5	8	15	18	61
	DFIT (invention)	0	0	0	0	0	0	0	1	2	1	7	11	28
	Grid/control	0	0	0	0	0	0	0	0	2	0	1	5	15
	Grid/Control (invention)	0	0	0	0	0	0	0	0	1	0	0	3	8
	Offshore	0	0	0	0	0	0	0	0	0	0	0	0	19
	Customized	0	0	0	0	0	0	0	0	4	0	7	0	0
Suzlon	Suzlon	0	0	0	0	0	1	1	4	6	11	11	13	14
	Incl. REpower	0	1	2	17	21	17	29	31	46	38	54	45	44
	DFIT	0	0	0	0	0	0	0	4	1	9	9	6	10
	Incl. REpower	0	0	1	1	2	4	8	18	21	19	30	14	26
	Grid/control	0	0	0	2	8	7	4	17	16	13	25	15	14
	offshore	0	0	0	0	1	1	0	0	2	1	2	0	3
	Customized	0	0	0	0	0	0	0	0	2	0	2	0	0
Vestas	Total	14	10	28	28	22	22	63	118	193	231	252	217	83
	DFIT	2	5	8	8	3	3	6	61	126	170	192	170	69
	Grid/control	0	0	0	2	6	1	12	33	50	89	115	81	33
	offshore	0	0	0	0	0	0	0	4	4	5	17	16	13
	Customized	0	0	0	0	0	0	0	0	0	0	0	0	0
Enercon	Total	75	40	27	21	15	7	7	1	7	12	52	43	51
	Direct-drive	10	8	8	10	3	2	1	1	5	4	13	24	25
	Grid/control	2	2	0	2	0	1	0	0	1	2	5	14	12
	offshore	1	0	2	2	2	0	0	0	0	0	0	0	0
	Customized	0	0	0	0	0	0	0	0	0	0	0	0	0
Siemens	Total	12	2	12	6	5	7	9	9	26	27	67	60	52
	DFIT	1	1	6	4	2	2	4	5	19	24	56	53	36
	Grid/control	0	0	0	0	0	0	0	1	3	4	4	9	5
	offshore	0	0	0	0	1	0	0	1	3	1	0	5	2
	Customized	0	0	0	0	0	0	0	0	0	0	0	0	0

Annex B Citation matrix for the full network

Cited	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Citing Values >= 0	AERODYN	DONGFANG	ENERCON	ENVISION	GAMESA	GE	GOLDWIND	GUODIAN	MINGYANG	NORDEX	SHANGHAI	SIEMENS	SINOVEL	SUZLON	VENSYS	VESTAS	XEMC
1 AERODYN	22	0	41	6	57	82	3	3	4	44	4	63	4	72	4	85	8
2 DONGFANG	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
3 ENERCON	32	1	157	14	142	325	9	11	10	151	6	293	18	230	8	330	28
4 ENVISION	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1
5 GAMESA	3	0	27	8	45	88	2	1	6	35	1	83	4	57	5	108	5
6 GE	26	1	146	15	168	387	11	18	12	191	6	357	25	272	6	413	22
7 GOLDWIND	0	0	0	0	0	1	2	0	1	0	0	2	1	0	0	1	2
8 GUODIAN UNI	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1
9 MINGYANG	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	1	3
10 NORDEX	3	1	18	2	22	53	4	3	0	38	0	53	1	63	0	69	4
11 SHANGHAI	0	0	0	0	0	0	0	0	3	0	0	0	1	0	0	2	0
12 SIEMENS	19	1	101	5	78	187	9	7	4	83	6	206	13	128	4	194	19
13 SINOVEL	0	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	1
14 SUZLON	8	1	45	6	51	118	6	3	3	75	1	112	11	121	3	144	6
15 VENSYS	12	0	15	0	14	20	2	2	1	8	2	35	1	14	8	17	9
16 VESTAS	20	0	88	7	129	254	6	9	4	118	5	234	13	145	2	318	14
17 XEMC	2	0	1	0	2	3	0	1	1	2	0	7	0	3	3	5	4

(Note: self-citations are shown in bold.)

Annex C Summary of patent network size

The frequency statistics of the three networks mainly contain the number of nodes (firms), the number of citations (links), the number of self-citations (loops), and the maximum value of links (max citations between two firms).

Time\Indicators	Number of firms	Citations (links)	Self-citations (loops)	Max value of links
1993-2006	16	4315	722	225
2007-2012	17	2942	609	209
Full time	17	7211	1318	413

Annex D Other supporting materials

Additional supporting materials can be found in supplementary files (or refer to the author, zhou_yuan@tsinghua.edu.cn), including patent searching strategies (Appendix 1), top-ten citation records for sample firms (Appendix 2), and the co-patenting matrix (Appendix 3).